Diesel Engine Air-borne Acoustic Signals Analysis Using Continuous Wavelet Transform

A. Albarbar

Advanced Industrial Diagnostics Centre, Digital Signal Processing & Novel Algorithms Research Group, School of Engineering, Manchester Metropolitan University, Manchester, UK

a.albarbar@mmu.ac.uk

Abstract

This paper studies the characteristics of Diesel engine air-borne acoustic signals using time-frequency domain techniques. One analysis technique is investigated: Continuous Wavelet Transform (CWT) which is reviewed from the mathematical point of view, based on its developmental stages, drawbacks and the subsequent improvements.

The detection capabilities of this technique are evaluated using air-borne acoustic signals collected from diesel engine in acoustically untreated laboratory.

Some engine conditions and faults are investigated using CWT techniques. The achieved results prove the technique's sensitivity to engine's speed and load variations. More important, the CWT shows excellent capabilities in detecting engine's injection process and lubrication related faults at early stages. At the end of the paper, summary is given.

Keywords

Air-borne Acoustic Signals; Continuous Wavelet Transform (CWT); Diesel Engines; Engine Noise

Introduction

Diesel engine air-borne acoustic signatures are rich in information about its operating parameters and physical condition. Unfortunately, due to the number of vibro-acoustic sources, environmental effects and the large number of physical degrees of freedom of the engine, these signatures are very complex and may be highly corrupted so that the identification procedures may converge slowly, if at all. A number of research works have focused on ways to extract useful information about the diesel engine operating conditions and health from the air-borne acoustic signals in a normal, acoustically untreated laboratory environment, without any sound measurement precautions [*Albarbar* et al, 2010, *Albarbar* et al, 2010, *Albarbar* et al, 2008, *Albarbar* et al, 2007].

Engine's air-borne acoustic signals are produced by a reciprocating engine and contain many sources that possess different frequency distributions and also occur at different times, and hence it is sensible to reveal this information via time-frequency analysis methods. The time-frequency method is very useful in that most engine airborne acoustic signals are related to events such as combustion and valve operations which have fixed occurrence times determined by the crank mechanism. By performing time-frequency analysis these events can be identified according to their occurrence in both time and frequency [*Chiollaz* et al, 1993]. Current methods of time-frequency distribution include short-time Fourier transform (STFT) [*Cohen* et al, 1989], wavelet transform (WT) [*Ball* et al, 2000], bilinear time-frequency distribution (BTFD) [*Daubechies* et al, 1992]. STFT and WT belong to linear time frequency transforms (LTFD).

Wavelet analysis techniques map a signal onto a joint time-frequency (scale) plane and are sensitive to transient signals. Winger-Ville distribution (WVD), Choi-Williams distribution (CWD) and Born-Jordan distribution (BJD) are the most commonly used BTFD techniques [*Cohen* et al, 1989]. When applied to the processing of transient signals, these distributions generally produce large ripples on the envelope of the transient signal component, which can result in the loss or the distortion of some information valuable for fault detection and condition monitoring, such as peak amplitude and time of occurrence [*Wu* et al, 2006]. In general, both LTFD and BTFD are superior to the conventional Fourier based frequency analysis by giving better time and frequency resolutions and locations.

In this paper, the continuous wavelet transform (CWT) including the mathematical equations behind it is described, some important properties of this technique are summarised and finally a performance evaluation

of the techniques is made using real acoustic signals measured from Diesel engine running under different operating and health conditions.

Wavelet Transform (WT)

This section presents the definition and the principles of continuous wavelet transform and the Morlet wavelet technique. It is well known that the wavelet transform is capable to detect both stationary and transitory signals. This made CWT be widely recognized as an effective technique for machinery fault diagnosis using sound and vibration signals. The continuous wavelet transform (CWT) is a time-frequency decomposition which links a time (or space) domain function to its time-scale wavelet domain representation. The concept of scale is broadly related to frequency. Small scales relate to short duration, high frequency features and correspondingly, large scales relate to long duration, low frequency features [*Goupillaud* et al, 1984]. The CWT of a real valued time signal *f (t)* can be described as follows [*Daubechies* et al, 1992, *Smith* et al, 2000]:

$$(CWTx)(a,b) = \frac{1}{\sqrt{a}} \int_{\infty}^{-\infty} f(t)\psi\left(\frac{t-y}{x}\right)dt \qquad (1)$$

Equation (1) means that the CWT of the *f (t)* is the product of this analysed signal and a family function, which could be defined as:

$$\psi_{x,y} = \frac{1}{\sqrt{x}}\psi\left(\frac{t-y}{x}\right) \qquad (2)$$

Where $\psi(t)$ in the space $L^2(\Re)$ is called the wavelet function, x and y are called the dilation and translation parameters.

The wavelet function should satisfy two conditions:

1- The $\psi(t)$ and its Fourier transform, $\hat{\psi}(f)$, satisfy the admissibility condition

$$C_\psi = \int_{-\infty}^{\infty} \frac{|\hat{\psi}(f)|^2}{|f|} df \langle \infty \qquad (3)$$

This condition ensures that the reconstruction of the original signal is possible from the *CWT*, which could be obtained by

$$f(t) = \frac{2}{C_\psi} \int_{-\infty}^{\infty}\int_{0}^{\infty} (CWTf)(x,y)\psi^{x,y}(t)\frac{dxdy}{x^2} \qquad (4)$$

2- A wavelet $\psi(t)$ is a function of zero average

$$\int_{-\infty}^{\infty} \psi(t) = 0 \qquad (5)$$

This condition ensures that the mother wavelet has zero mean-contains no D.C. components-and decays rapidly [*Goupillaud* et al, 1984].

The continuous wavelet transform CWT and its coefficients comprises time information and scale bands. In the *CWT*, the dilation and translation parameters (*x and y)* are subjected to continuous variation. This makes the use of CWT complex and timing consuming. Discretisation of the dilation and translation parameters helps in reducing the complexity and calculation time of the CWT. Hence, a number of wavelet transforms could be generated.

The CWT of a digital signal is defined as follows:

$$CWT_x = \sum_{m=0}^{N-1} X_m \psi^* \left[\frac{(m-n)\Delta t}{xj}\right] \qquad (6)$$

Where X_m is the discrete of the continuous signals, $t = m\Delta t$, $y = n\Delta t$, where m, $n = 0,1,2,\ldots,N-1,N$, is the data samples and Δt is the sampling time.

The signal amplitude varies with time based on the values of *j* and *n*. Therefore, CWT_x represents signal's distribution in time and frequency domains. The Morlet wavelet has the capability to determine both amplitude and phase information.

The Morlet wavelet is powerful in detecting impulse components within mechanical signals due to its shape [*Wu* et al, 2006]. Equation 7 represents the mathematical description of the Morlet wavelet:

$$\psi(t) = \pi^{-1/4} e^{i\omega_1 t} e^{-t\ /2} \qquad (7)$$

Where ω_1 is the non-dimensional frequency. The function of a Morlet wavelet is an exponentially sinusoidal signal. Therefore, its shape can be adjusted in order to adapt to the various sinusoidal waveforms that are commonly found in many dynamical systems [*Daubechies* et al, 1992].

Mother wavelet selection depends on the application. In case of diesel engine airborne acoustic signals, this procedure is vital to maximise the ability to detect transients and high frequency bands. There are a number of wavelets available to choose from, including Gabor, Harr, Newland, Mexican hat, Mallat.

Because of its ability to detect transient events; the Morlet mother wavelet is used in the CWT in this paper.

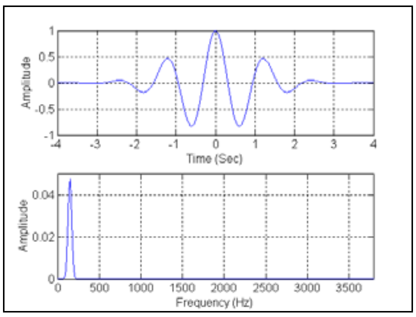

FIGURE 1 MORLET WAVELET (UPPER TRACE) AND ITS POWER SPECTRUM (LOWER TRACE)

The Morelet wavelet as shown in Figure 1, consists of a plane wave modulated by a Gaussian function, and its representation in time domain $\psi(t)$ and in frequency domain $\hat{\psi}(s\omega)$ are given in Equation (8).

$$\psi_0(t) = \pi^{-1/4} e^{j\omega_0 t} e^{-t^2/2}$$
$$\hat{\psi}(s\omega) = \pi^{-1/4} e^{-(s\omega-\omega_0)^2/2}, \omega > 0, \tag{8}$$

Where ω_0 is called the centre frequency and determines the location of the Morlet wavelet [*Fan* et al, 2007].

Implementing *CWT* as expressed in Equation (1); which is the convolution of the time signal *f (t)* with the conjugate wavelet function $\psi(t)$, is a long process. To reduce complexity and duration, the *CWT* is implemented in the frequency domain as shown in Equation (9).

$$(CWTf^{\wedge})(x,y) = \frac{\sqrt{x}}{2\pi} \int_{-\infty}^{\infty} f^{\wedge}(\omega) e^{i\omega y} \psi^{\wedge}(\omega) d\omega \tag{9}$$

Where $f^{\wedge}(\omega)$ and $\psi^{\wedge}(\omega)$ are the Fourier transforms of the time domain signals $f(t)$ and $\psi(t)$ respectively. Equation (9) is simply the inverse Fourier transform of the product between $f^{\wedge}(\omega)$ and $\psi^{\wedge}(\omega)$, which could be accelerated by the use of a FFT.

Test Rig and Instrumentation

The tested engine is medium size Ford Diesel engine equipped with a number of transducers, see Figure 2. Engine's air-borne acoustic signals were measured using a condenser microphone. Combustion pressure, vibration, speed, top dead centre (TDC) position, temperature and load measurements were also collected.

Before the pressure sensor and accelerometer signals were fed to the Analogue-to-Digital Converter (ADC), they passed through a B&K type 2635 charge amplifier to condition the signal. The charge amplifier compensates for the reduction in transducer sensitivity due to the use of long cables, filters out unwanted signal components and amplifies the signal. The charge amplifier also converts the high-impedance output signal into a low-impedance voltage signal [*Albarbar* et al, 2007].

The in-cylinder pressure signal used to monitor combustion conditions was obtained from a Kistler type 6125A piezoelectric pressure sensor. The flywheel TDC trigger signal is used to set the start time of data collection so that each data segment is measured at an exact crank position. This is to ensure accurate time domain averaging and rearrangement of data segments [*Albarbar* et al, 2010]. A second trigger signal, from the flywheel gear encoder, is used to measure engine speed. The external load is measured with a load cell behind the hydraulic dynamometer. All signal are fed into 16-bit data acquisition card and the signal processing was carried out offline on MatLab.

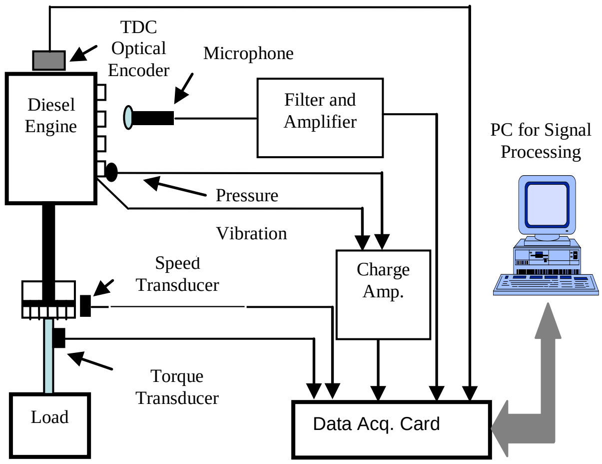

FIGURE 2 SCHEMATIC DIAGRAM OF ENGINE TEST SYSTEM

Cwt of Engine Airborne Acoustic Signals

Figure 3 shows the acoustic waveform of the diesel engine in the time domain and the continuous wavelet transform (CWT). From the CWT representation, we can see clearly four peaks representing the combustion events of the engine cylinders in the firing order from left to right (3, 1, 2, and 4).

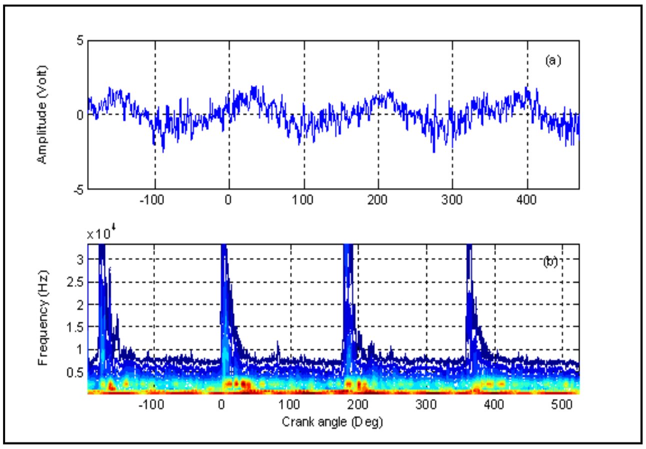

FIGURE 3 AIRBORNE ACOUSTIC SIGNAL REPRESENTATIONS AT ZERO LOAD AND 1000 RPM (a) TIME DOMAIN (b) CWT CONTOUR PLOTS.

Cyclic averaging is very useful in random noise cancellation, which is why the averaging was applied on the CWT to prevent the loss of high frequency components [*Ball* et al, 2000, *Fan* et al, 2007]. The spectral analysis shows that the major part of the energy is located in the lower frequencies (below 5

kHz), which can be seen more clearly in the CWT representation, as well it can be observed that the peak of the CWT extends to around 35 kHz. Figures 4 and 5 represent CWT of the engine airborne acoustic signals for different loads and engine speeds. The heights of the combustion peaks are proportional to the engine load and speed, confirming that the engine airborne acoustic signals are load and speed dependent.

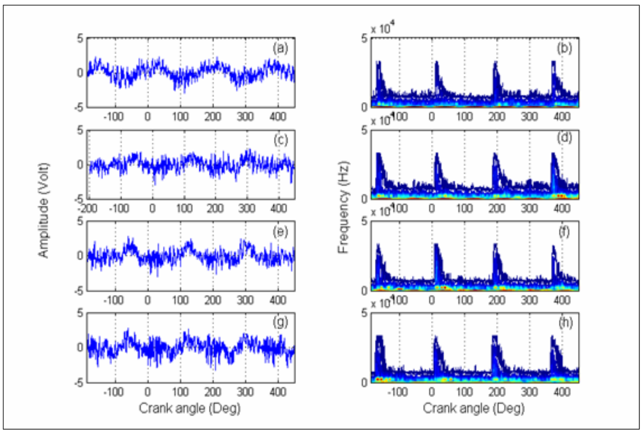

FIGURE 4 AIRBORNE ACOUSTIC SIGNAL FOR LOAD VARIATION: (a) ZERO LOAD, (b) CWT OF ZERO LOAD, (c) LOAD OF 20 NM, (d) CWT OF 20 NM, (e) LOAD OF 40 NM, (f) CWT OF 40 NM, (g) LOAD OF 60 NM AND (h) CWT OF 60 NM.

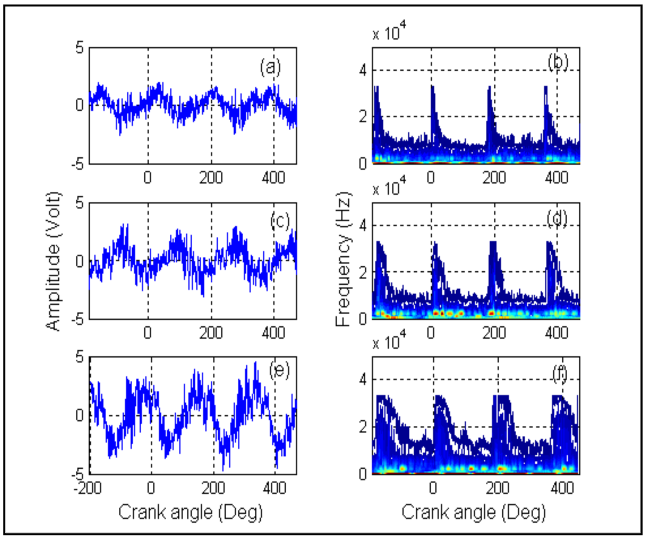

FIGURE 5 AIRBORNE ACOUSTIC SIGNAL FOR ENGINE SPEED VARIATION: (a) 1000 RPM, (b) CWT OF 1000 RPM, (c) SPEED OF 1500 RPM, (d) CWT OF 1500 RPM, (e) SPEED OF 2000 RPM, (f) CWT OF 2000 RPM.

Fault Detection and Diagnosis

According to the literature review, the CWT is able to represent both low and high frequency bands energy levels with desirable resolution.

Figure 6 shows the CWT of the engine airborne acoustic signals under five injector opening pressure sets; and the healthy injection pressure (250 bar) sharp increase in the acoustic signal around zero degree (TDC) at the combustion onset as shown in Figure 6(a).More sharp and higher amplitude combustion excitation and about three degrees delay are observed when this injection pressure increased to 260 bars (Figure 6(b)). The symptoms became clearer when the injection pressure increased to 270 bar (Figure 6(c)).

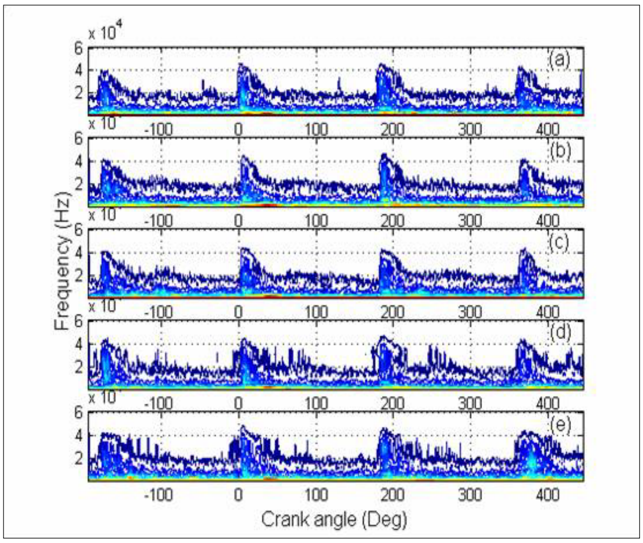

FIGURE 6 CWT CONTOUR PLOTS AT 1000 RPM AND 30 NM LOAD WITH FIGURE 6 CWT OF THE ENGINE AIR-BORNE ACOUSTICS RUNNING (a) HEALTHY, (b) INJECTION PRESSURE INCREASED TO 260 BAR, (c) INJECTION PRESSURE INCREASED TO 270 BAR, (d) INJECTION PRESSURE REDUCED TO 240 BAR AND (e) INJECTION PRESSURE REDUCED TO 230 BAR.

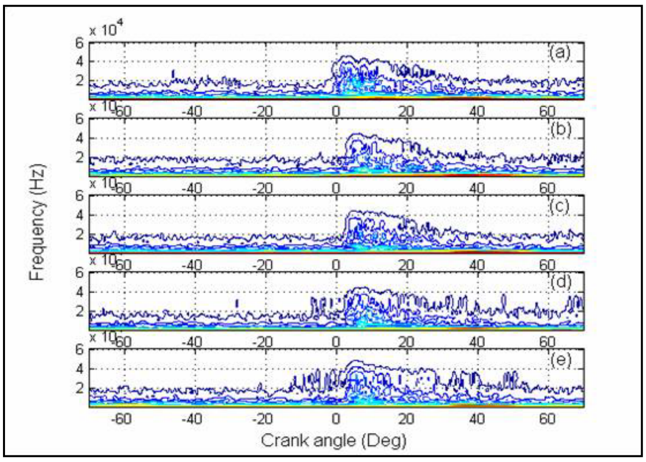

FIGURE 7 CWT CONTOUR PLOTS LIMITED TO RANGE OF CRANK ANGLES FROM -60º TO + 60º, FOR CYLINDER NUMBER 1 AT 1000 RPM AND 30 NM LOAD WHEN ENGINE RUNNING AT (a) HEALTHY CONDITION; (b) INJECTION PRESSURE INCREASED TO 260 BAR; (c) INJECTION PRESSURE INCREASED TO 270 BAR; (d) INJECTION PRESSURE REDUCED TO 240 BAR; (e) INJECTION PRESSURE REDUCED TO 230 BAR.

Figure 6(d), represents the airborne acoustic signals around cylinder no. 1 when the injection pressure was reduced to 240 bars; and as well a longer and unstable combustion period is observed. By decreasing the injection pressure to 230 bars, the combustion became more affected and deteriorated. In both cases, injection

was brought forward and as a consequence, combustion occurred earlier. Figure 7 shows only the signal around cylinder number one.

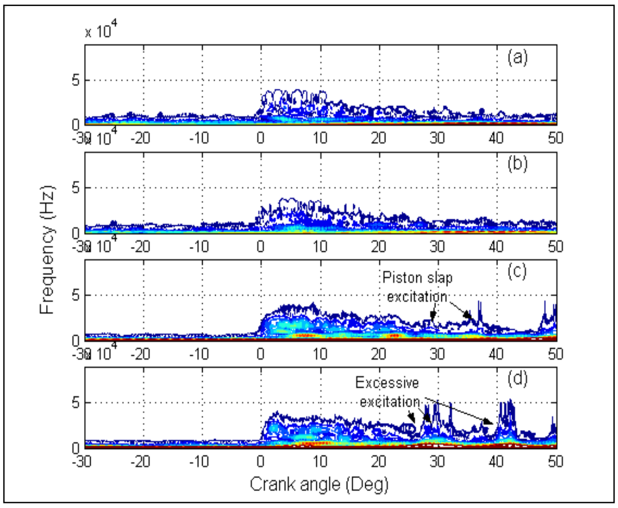

FIGURE 8 CWT CONTOUR PLOTS AT 1000 RPM AND 30 N.M. LOAD WHEN ENGINE RUNNING (a) HEALTHY - 100% OIL LEVEL, (b) HEALTHY - 90% OIL LEVEL (c) HEALTHY - 80% OIL LEVEL, AND (d) HEALTHY - 70% OIL LEVEL.

A single microphone facing cylinder number 1 was used to collect the airborne acoustic signals for different oil levels; and the oil level was decreased from healthy level (100% level) to 70% level in steps of 10%, as shown in Figure 8which indicates the CWT representation for cylinder number 1 in the case of healthy conditions with reduced oil levels. Piston slap excitations are seen around 10^{o}, 15^{o} and 30^{o} after TDC. These excitations increase as the oil level was reduced to 80% and 70% of the manufacturer's recommended level, see Figure 7 (c) and (d). Another way to extract more information at higher frequency bands was described by Ball [*Ball* et al, 2000]. In their paper, Ball stated that it was found that the lower amplitude contours of the CWT plots characterised the combustion processes the best.

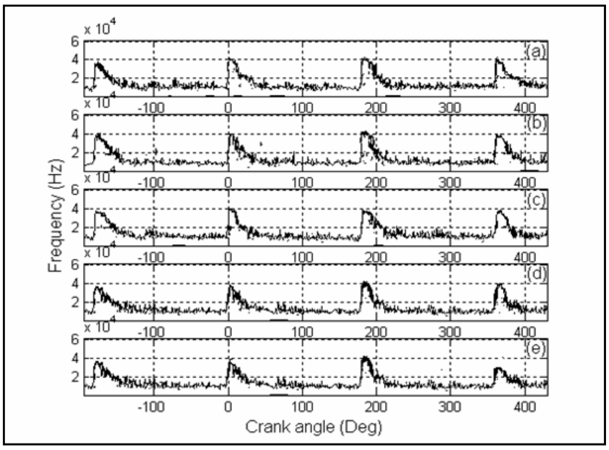

FIGURE 9 CONTOUR PLOTS OF (a) 250 BAR (HEALTHY) (b) 245 BAR INJECTION PRESSURE; (c) 240 BAR INJECTION PRESSURE; (d) 235 BAR INJECTION PRESSURE; (e) 230 BAR INJECTION PRESSURE.

Figure 9 represents 27% contour plots used to extract more useful information about combustion process at higher frequency amplitudes under lower injection pressure reductions.

The injection pressure of cylinder number 1 was reduced from 250 bars (healthy) to 230 bars in steps of 5 bar as shown in Figure 9. The peak of the combustion of cylinder pressure is lowered by decreasing the injection pressure.

Summary

In this paper, Diesel engine airborne acoustics were investigated in the time-frequency domain; which was carried out using continuous wavelet transform (CWT) as a linear time-frequency technique. The theoretical background of this technique was firstly explained in detail. The CWT has the ability to adapt its resolution to satisfy signal processing needs while analysing different frequency bands and although the resolutions in both the time and frequency domains could not be obtained simultaneously, it is adequate in that it gives a much better resolution in one domain.

The Morlet wavelet was selected as a mother wavelet because of its better resolution than the other wavelets. In order to accelerate the computation time, the CWT was implemented in the frequency domain.

The results from CWT analysis of the air-borne acoustic signals, for an engine running under faulty conditions, reveal its advantages in fault detection, as abnormal combustion related faults of different severity were identified by the time-frequency representation of the acoustic signals in the high frequency bands. Oil lubrication level related problems could also be detected using this technique; which open doors for other oil related conditions such as quality to be monitored.

REFERENCES

Albarbar, A., Gu, F., Ball, A. and Starr, A., 2010, Diesel Engine Fuel Injection Monitoring Using Acoustic Measurements and Independent Component Analysis, 2010 . Journal of Measurement, 43 (10), 1376-1386.

Albarbar, A., Gu, F., Ball, A. and Starr, A., 2010, Acoustic Monitoring of Engine Fuel Injection Based on Adaptive Filtering Techniques, Applied Acoustics, 71(17), 1132–1141.

Albarbar, A., Gu, F., Ball, A., Starr, A., 2008, On Acoustic Measurement Based Internal Combustion Engines

Condition Monitoring. Journal of Non-destructive Testing, 49 (8), 30-34.

Albarbar, A., Gu, F., Ball, A. and Starr, A., 2007, Internal Combustion Engine Lubricating Oil Condition Monitoring Based on Vibro-acoustic Measurements. Journal of Non-Destructive Testing. 49 (7), 715-718.

Ball, A., Gu, F., Weidong, L., 2000. The Condition Monitoring of Diesel Engines using Acoustic Measurements, part 2: Fault Detection and Diagnosis, SAE Special Publication SP 1501.

Chiollaz, M., and Faver, B., 1993. Engine Noise Characterisation with Wigner-Ville Time-Frequency Analysis. Journal of Mechanical Systems and Signal Processing. 75,375-400.

Cohen, L.. 1989. Time-Frequency Distributions – A Review, Proceeding of the IEEE, Vol.77, No.7.

Daubechies, I., 1992. Ten Lectures on Wavelets. Philadelphia: Society for Industrial and Applied Mathematics.

Fan, Y., Zheng, G., 2007. Research of High-Resolution Vibration Signals Detection Technique and Application to Mechanical Fault Diagnosis, Journal of Mechanical Signal Processing. 678–687.

Goupillaud, P., Grossman, A., Morlet, J., 1984. Cycle-octave and Related Transforms in Seismic Signal Analysis', Geoexploration 23, 85-102.

Lin, J., Zuo, M., 2003. Gearbox Fault Diagnosis Using Adaptive Wavelet Filter. Mechanical Systems and Signal Processing; 17(6):1259–69.

Smith, T., 2000. The Application of the Wavelet Transform to the Processing of Aeromagnetic Data, PhD Thesis, The University of Western Australia.

Wang, J., McFadden, P., 1996. Application of Wavelet to Gearbox Vibration Signals for Fault Detection, Journal of Sound and Vibration 192 (5) (1996) 927-939.

Wu, J., Chen, J., (2006), Continuous wavelet transform technique for fault signal diagnosis of internal combustion engines", NDT&E International 39 (2006) 304–311.

Alhussein Albarbar has over 21 years working experience with both industry and academia. He is currently holding a post of associate professor in mechanical engineering with School of Engineering, Manchester Metropolitan University. Dr Albarbar has supervised over 17 industrially sponsored Master's and Doctoral research and development projects. He has widely published; over 57 research papers in refereed journals and international conference proceedings, a book and a book chapter. His current research activities include renewable power systems, smart sensing, intelligent monitoring algorithms and electromechanical plants diagnostics.